# DSOGI-PLL Based Power Control Method to Mitigate Control Errors Under Disturbances of Grid Connected Hybrid Renewable Power Systems

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***Abstract.*** *The control of power converter devices is one of the main research lines in interfaced renewable energy sources, such as solar cells and wind turbines. Therefore, suitable control algorithms should be designed in order to regulate power or current properly and attain a good power quality for some disturbances, such as voltage sag/swell, voltage unbalances and fluctuations, long interruptions, and harmonics. Various synchronisation techniques based control strategies are implemented for the hybrid power system applications under unbalanced conditions in literature studies. In this paper, synchronisation algorithms based Proportional-Resonant (PR) power/current controller is applied to the hybrid power system (solar cell + wind turbine + grid), and Dual Second Order Generalized Integrator-Phase Locked Loop (DSOGI-PLL) based PR controller in stationary reference frame provides a solution to overcome these problems. The influence of various cases, such as unbalance, and harmonic conditions, is examined, analysed and compared to the PR controllers based on DSOGI-PLL and SRF-PLL. The results verify the effectiveness and correctness of the proposed DSOGI-PLL based power control method.*

## Keywords

***DSOGI, grid disturbances, power quality, PR controller, renewable energy sources.***

## 1. Introduction

The integration of Hybrid Renewable Energy Resources (HRES), such as wind turbines and solar cells, into electric networks is a powerful and efficient way to meet the growing energy demand and minimize environmental restrictions, such as weather conditions, wind speed and solar irradiation, and depletion of fossil fuels reserves [1] and [2]. Grid connection systems provide reliable means for customers to use renewable energy sources, such as solar cells and wind turbines. The HRES are generally connected to electric grids via three-phase voltage source inverters [3]. The power converter devices are widely used as interfaces for hybrid resources [4]. The power converter devices improve efficiency and performance of the power systems and provide reliable electric power processing/flow. However, the grid disturbances lead to power quality problems, such as voltage unbalances, voltage sag/swell, voltage fluctuations, phase faults and harmonic pollution, in grid-connected systems. Therefore, an appropriate control method with synchronization technique is required to overcome these problems.

The synchronization techniques play an important role in voltage sag/swell detection and various controller based applications under unbalanced conditions [5]. In literature studies, various Phase-Locked Loop (PLL) techniques based control methods have been projected and implemented in power converters interfacing the HRES under grid faults. In [6], Moving Average Filter (MAF) is integrated to enhance the detection of fundamental active power currents and the dynamic performance of power/current control loop. In [7], modified control method utilizes Enhanced Phase-Locked-Loop (EPLL) technique to regulate DC link voltage under unbalanced grid conditions. Multivariable Filters (MFV) based PLLs are used to determine the reference current for the active power filter in order to improve the power quality and compensate reactive power required by nonlinear load, and it is also used as highly selective harmonic filtering [8] and [9]. In [10], [11] and [12], Second-Order Generalized Integrator

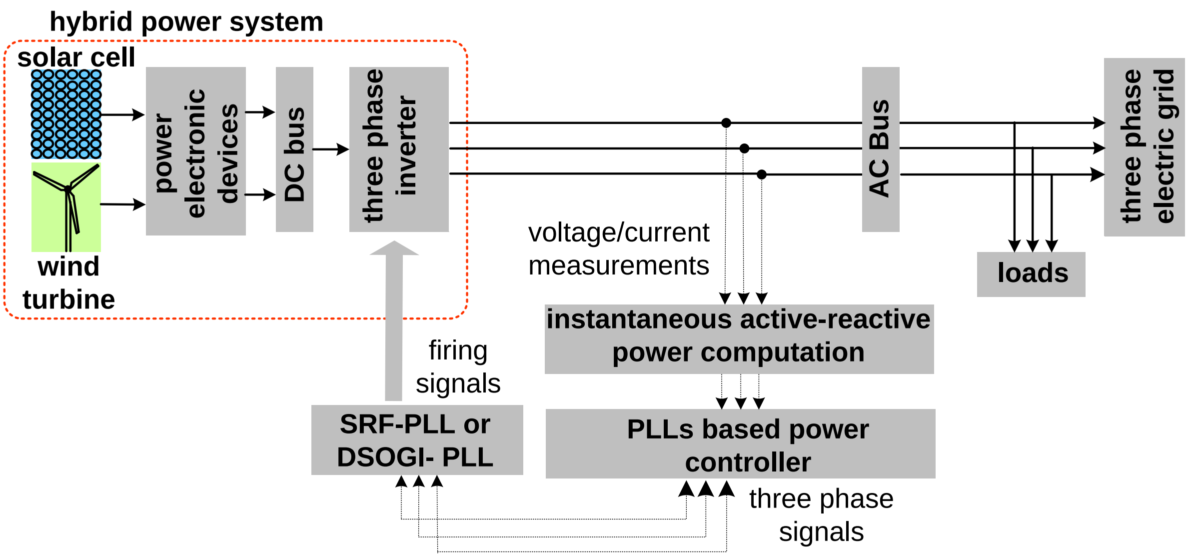


**Fig. 1:** SRF-PLL or DSOGI-PLL based power controller in hybrid power system application.

(SOGI) with frequency adaptation based Proportional Resonant (PR) controller is proposed to eliminate harmonic components in single-phase grid-connected inverter. In [13], the dual SOGI-PLL (DSOGI-PLL) is used for application of shunt active filter. Synchronisation algorithms based power controller in hybrid power system applications is shown in Fig. 1.

Generally, the classical PLL (SRF-PLL) based PR controller ensures high performance to mitigate harmonic components in hybrid power systems and has fast dynamic response under balanced conditions. It can also achieve an infinite gain at low frequencies and compensate harmonics at selected frequencies [14], [15] and [16]. However, it is not enough to reduce ripple in power, current and voltage signals under grid disturbances. It is also sensitive to frequency variations. PR controller based on various synchronisation techniques can be used in many applications [17].

In this paper, proposed PR power/current controller based on DSOGI-PLL technique provides a solution for power quality problems caused by grid disturbances, such as voltage sag/swell and voltage unbalances. In particular, although the conventional PLL based PR controller ensures good performance under balanced condition, it has poor performance under unbalanced and distorted grid conditions. In order to solve these problems, integration of DSOGI-PLL into PR power controller is proposed. Various cases of DSOGI-PLL based PR controller are analysed and examined. To observe effectiveness and availability of DSOGI-PLL based PR controller, it is compared with SRF-PLL based controller.

The remaining of the paper is structured as follows. Following the introduction, hybrid power system sources are investigated and analysed in Sec. 2. The synchronization techniques for power controllers are analysed in detail in Sec. 3. In Sec. 4. proposed power controller method is discussed under grid disturbances. Testing of the influence of various case studies on the mentioned controllers is presented, analysed and compared in Sec. 5. Section 6. summarizes the conclusion derived from this study.

# 2. Hybrid Power System Sources

## 2.1. Solar Cell

The electric behaviour of a solar cell can be modelled and analysed by a nonlinear current source [18]. The current source which is driven by sunlight is connected with a real diode in parallel (Fig. 2). The forward current could flow through the diode from p-side to n-side with little loss. However, if the current flows in reverse direction, only little reverse saturation current could get through [19].

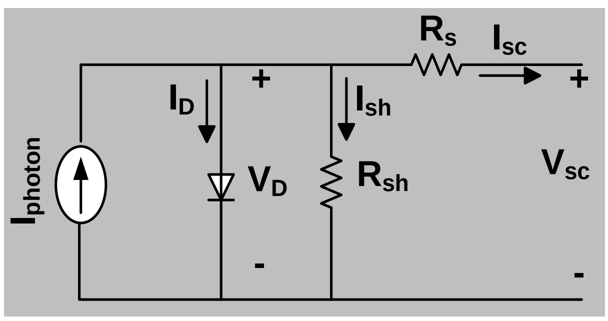


**Fig. 2:** Equivalent circuit for a solar cell.

$R_s h$ is the shunt resistance which accounts for leakage current [20], and $R_s$ is the internal resistance of the cell. Where $I_p h$ is the photon current, $I_o$ is the reverse saturation current, $V_s c$ is open circuit voltage, $k$ is the Boltzmann's constant, $q$ is the charge of an electron, and $T$ is the operating temperature of a cell. All the equations for modelling a solar cell are analysed based on the equivalent circuit. The relationship between solar cell current $I_s c$ and voltage is given by following equation Eq. (1) [21] and [22].

$$I_{sc} = I_{ph}(1 + C_0(T - 237.15)) - I_o \cdot \left(e^{\frac{q(V_{sc}+I\cdot R_s)}{nkT}} - 1\right) - \frac{(V_{sc} + I \cdot R_s)}{R_{sh}}. \quad (1)$$

In order to increase the efficiency of a solar cell under various weather conditions, Maximum Power Point Tracking (MPPT) is applied to the control of solar cell connected boost converter. The solar cell output power is given by Eq. (2);

$$P_{sc} = \eta \cdot V_{sc} \cdot I_{sc}. \quad (2)$$

A solar cell based on the single diode model is modelled and simulated by using PSCAD/EMTDC software. The simulations for P–V and I–V characteristics of a solar cell are depicted in Fig. 3 (at 1000 W·m$^{-2}$ and 25 °C). MPPT algorithm is used to get the maximum output power for any given solar irradiation and temperature.

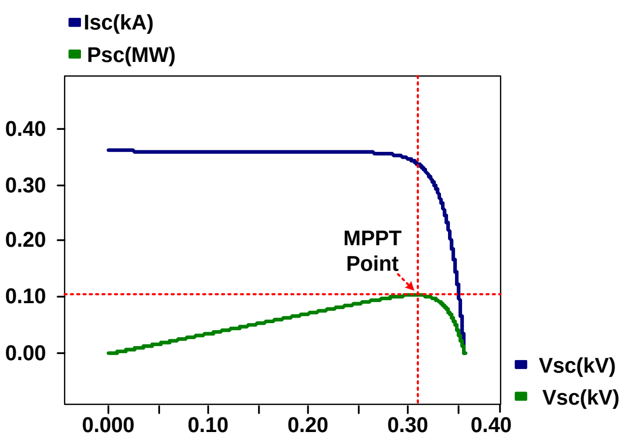


**Fig. 3:** P-V and I-V characteristics of solar cell.

## 2.2. Wind Turbine

The kinetic energy of the wind is extracted by wind turbines that transfer the momentum of air passing through the wind turbine rotor blades. The mechanical power is captured by a wind turbine. The mechanical model of a permanent magnet synchronous generator is used in wind power system. The kinetic energy $E$ is the function of the flowing air mass $m$ and velocity $V_w$ [23] and [24];

$$E = \frac{1}{2} V_W^2. \quad (3)$$

The maximum measured power from a wind turbine is limited by Betz's law. Higher wind speed provides more energy. $v_a$ and $v_b$ are input and output turbine blades speeds, respectively. The wind power captured by a wind turbine is proportional to the rotor swept area $A_s$, the air mass density $\rho_{air}$, and the wind speed $V_w$ [25]. Available turbine input and output powers $P_{wt\_in}$ and $P_{wt\_out}$ are given by the Eq. (4) and Eq. (5), respectively [26];

$$P_{wt\_in} = \frac{1}{2} A_s \rho_{air} v_a^3, \quad (4)$$

$$\begin{aligned} P_{wt\_out} = \frac{\mathrm{d}E}{\mathrm{d}t} &= \frac{1}{2} A_s \rho_{air} v_a^3 \\ &= \frac{1}{2} A_s \rho \left(\frac{v_a + v_b}{2}\right)(v_a^2 - v_b^2). \end{aligned} \quad (5)$$

To estimate the output power of wind turbine, the power is limited by a power coefficient $C_p$. In order to simplify the model, the optimal value is used for the power coefficient $C_p$, such as $C_p = C_{p,op}$. The maximum power of WT based on power coefficient is given as follows [27];

$$P_{wt\_out} = \frac{1}{2} C_{p,op}(\lambda, \beta) \cdot A_s \cdot \rho_{air} \cdot V_w^3. \quad (6)$$

The wind turbine rotor power coefficient $C_p$ is generally a nonlinear function of tip speed ratio $\lambda$ and blade pitch angle $\beta$ [23]. The power coefficient $C_p$ is given by Eq. (7) as follows;

$$C_p(\lambda, \beta) = 0.5176 \left(\frac{116}{\lambda_i} - 0.4\beta - 5\right) \cdot e^{-\frac{21}{\lambda_i}} + 0.0068\lambda, \quad (7)$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{1 + \beta^3}. \quad (8)$$

The power coefficient represents the efficiency of wind turbine components. The maximum rotor power efficiency is not greater than a theoretical maximum value of 0.593, called Betz limit [23]. The maximum wind power $P_{wt_out}$ obtained from wind energy can be described by Eq. (6). This simply means that the maximum power may be achieved by power coefficient which varies wind speed, turbine blade angle and other parameters [28].

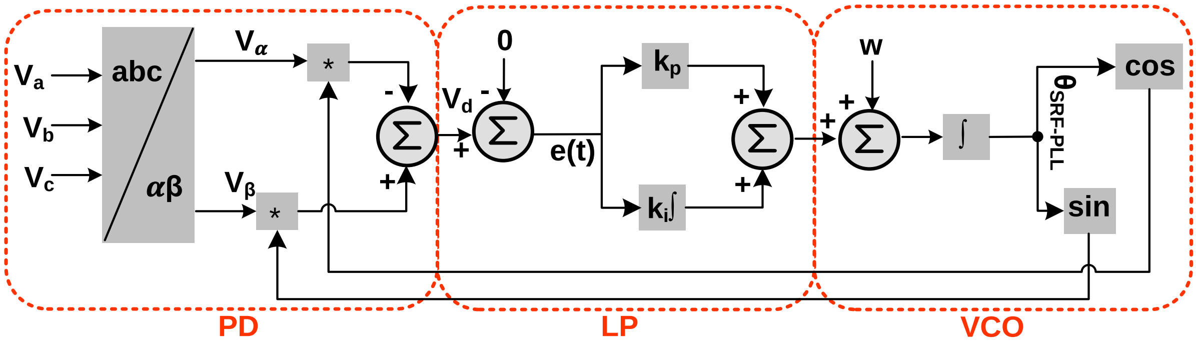


**Fig. 4:** The basic structure of SRF-PLL.

## 3. The Synchronization Techniques for Hybrid Power System

### 3.1. The Classical PLL

The basic structure of Synchronous Reference Frame Phase Locked Loop (SRF-PLL) consists of the Phase Detector (PD) block, Low Pass (LP) filter, and a Voltage Controlled Oscillator (VCO) as shown in Fig. 4. The classical PLL (SRF-PLL) based PR controller has good performance under balanced conditions. However, its structures are not designed to overcome such fluctuations and ripple in power and current controller as under asymmetry, unbalance, fault or contamination with higher harmonics [29]. Three phase signals $V_a$, $V_b$ and $V_c$ are converted to the stationary $V_\alpha$ and $V_\beta$ with Clarke transformation and then signals are processed by PLL to track phase/amplitude/frequency [30] and [31].

### 3.2. DSOGI Based PLL

The Second-Order Generalized Integrator (SOGI) based PLL is generally used for tracking frequency and phase measurements of alternating current signals in single-phase power converter devices [32]. The SOGI algorithm is also a very effective way to provide orthogonal signals $V_\alpha$ and $V_\beta$. Modified PLL methods based on the SOGI have been analyzed and provide good results to separate positive and negative sequences for reference current generation [33]. The DSOGI-PLL algorithm based on Dual Second-Order Generalized Integrator (DSOGI) provides high performance for phase detection under extreme, unbalanced and distorted grid operating conditions [34]. However, compared with dual EPLL under unbalanced conditions and harmonics injected into a grid, it has longer settling time, more harmonic errors, and ripple errors [35]. Under grid disturbances, the orthogonal signals $V_\alpha$ and $V_\beta$ are obtained by Clarke transformation to be used in PR controller. The application of SOGI-PLL in single-phase and three-phase systems is depicted in Fig. 5.

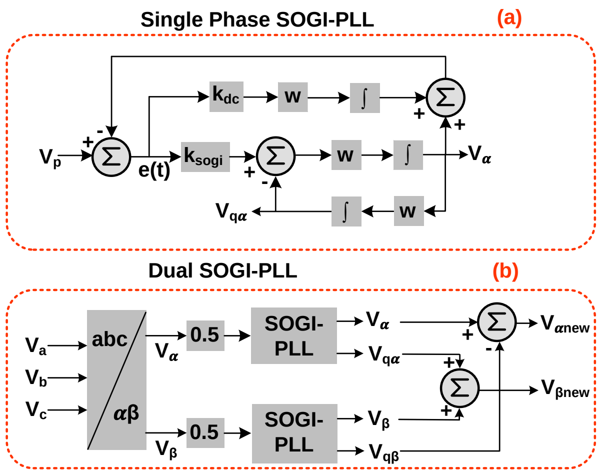


**Fig. 5:** The block diagram of SOGI based PLL, a) using in single-phase applications b) using in three-phase applications.

The closed-loop transfer functions of DSOGI-PLL are given as follows,

$$G(s) = V_\alpha(s)/V_p(s) = \frac{k_{sogi}\omega s^2}{\Delta s}. \tag{9}$$

The orthogonal signals are calculated by following equations;

$$V_{q\alpha}(s) = \frac{\omega}{s}V_\alpha(s), \tag{10}$$

$$G_1(s) = V_{q\alpha}(s)/V_p(s) = \frac{k_{sogi}\omega^2 s}{\Delta s}, \tag{11}$$

$$\Delta s = s^3 + (k_{sogi} + k_{dc})\omega s^2 + \omega^2 s + k_{dc}, \tag{12}$$

where $\omega$ is fundamental of an input signal, and DSOGI-PLL creates two orthogonal signals as outputs, $V_\alpha$ and $V_{q\alpha}$. The output $V_\alpha$ is in phase with the fundamental component of the input signal $V_p$. The gains $G_1(s)$ and $G(s)$ affect the bandwidth of SOGI. The variations of DSOGI parameter $k_{sogi}$ and DC offset parameter $k_{dc}$

can affect error signal and the dynamic response of the system.

In case of grid disturbances, DSOGI based PLL produces orthogonal signals to eliminate the impact of grid disturbances. With two SOGI, generated quadrature output signal $V_{q\alpha}$ is in phase with $V_\beta$, and $V_\alpha$ lags $V_{q\beta}$ with phase of 180°. Figure 6 shows that the orthogonal signals $V_\alpha$, $V_\beta$ obtained by Clarke transformation are in phase with $V_{\alpha new}$, $V_{\beta new}$ obtained by DSOGI-PLL.

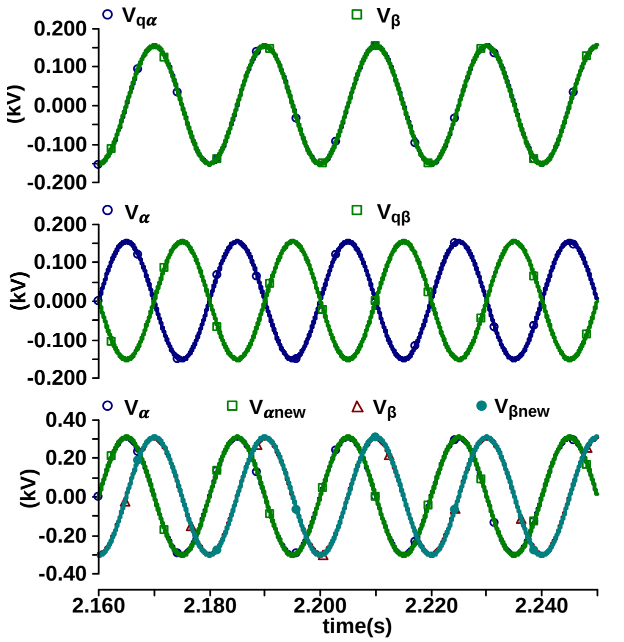


**Fig. 6:** The generated orthogonal signals under grid disturbances.

## 4. Proposed Power Controller Method

The stationary reference frame based Proportional-Resonant (PR) controllers [36] are normally used in power and/or current control applications such as grid interactive power converter devices because of their superior features. The classical PI controller has high gain values in DC systems and provides good performance in DC signal applications. However, the PI controller has low gain in AC signal applications and provides poor performance. Therefore, the PI controller cannot track the sinusoidal waveform without steady-state error. The main advantage of the PR controller is the transfer of the high gain feature of the PI controller from DC signals to AC signals [37]. The PR controller has a high infinite gain at the resonant frequency and has no gain at other frequency values. With this feature, PR controllers can be used in active power filter applications and DG power systems. They can track the harmonic reference signals, remove selected harmonic components and overcome stability problems [38], but they are sensitive to frequency variations and more complex than some other controllers, such as hysteresis and dead-beat controllers [39]. The classical PLL based PR power/current controller method has poor performance under unbalanced voltages and phase faults. For unbalanced conditions and the synchronization of a grid-tied inverter, the DSOGI-PLL based PR controller is presented in this paper (Fig. 7). The digital implementation of DSOGI-PLL based PR controller is suitable for a Digital Signal Processing (DSP) and Field Programmable Gate Array (FPGA) microprocessors.

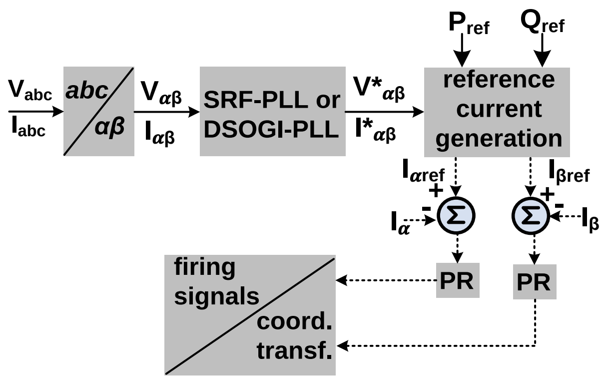


**Fig. 7:** PLLs based PR controller.

When PI controller in the synchronous reference frame is converted to the stationary reference frame, PR current controller is obtained. The equivalence between PI and PR controllers is proved by following equations [40].

$$V_{dq} = \begin{bmatrix} V_d \\ V_q \end{bmatrix} = [PI(t)] \cdot \Delta I_{dq} = \begin{bmatrix} PI(t) & 0 \\ 0 & PI(t) \end{bmatrix} \cdot \begin{bmatrix} i_d \\ i_q \end{bmatrix}. \quad (13)$$

Clarke transformations correspond to Park transformations; reference frame controller is expressed as follows;

$$V_{\alpha\beta} = \begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \begin{bmatrix} PR(s) & 0 \\ 0 & PR(s) \end{bmatrix} \cdot \begin{bmatrix} \Delta i_\alpha \\ \Delta i_\beta \end{bmatrix}. \quad (14)$$

$\omega_o$ is the grid fundamental angular frequency, and $k_i$ is a constant which is carefully chosen to change the controller's magnitude response vertically in Eq. (15) [36].

$$\Delta V_{\alpha\beta}/\Delta I_{\alpha\beta} = PR(s) = k_p + \frac{k_i \omega_c s}{s^2 + 2\omega_c s + \omega_o^2}. \quad (15)$$

The parameters of PR controller $k_p$, $k_i$ and $\omega_c$ indicate proportional and integral gains, and resonant frequency term, respectively. A non-ideal PR current controller has lower gain and wider bandwidth than ideal PR controller at resonant frequency [41].

As expressed in Eq. (13), PI controller is equivalent to PR controller in terms of current error cancellation and harmonic components removal. Furthermore, the simplicity of PR controller in the stationary reference frame can be implemented with DSP or FPGA due to its low mathematical computations [42]. Figure 7 depicts the block diagram of PR power/current controller based on SRF-PLL or DSOGI-PLL. In the current controller, the DSOGI–PLL based two PR controllers are used in the stationary frame to avoid complex coordinate transformation. The references of the current controller $I_{\alpha ref}$, $I_{\beta ref}$ are provided according to the instantaneous active reactive controller. By applying the Clarke transformations, the active and reactive power can be expressed as in Eq. (16), Eq. (17) and Eq. (18).

$$\begin{cases} I_{\alpha ref} = \dfrac{v_{\alpha}^{*} \cdot P_{ref} + v_{\beta}^{*} \cdot Q_{ref}}{v_{\alpha}^{2} + v_{\beta}^{2}}, \\ I_{\beta ref} = \dfrac{v_{\beta}^{*} \cdot P_{ref} - v_{\alpha}^{*} \cdot Q_{ref}}{v_{\alpha}^{2} + v_{\beta}^{2}}, \end{cases} \tag{16}$$

$$P = \frac{3}{2}(V_{\alpha}^{*} \cdot I_{\alpha}^{*} + V_{\beta}^{*} \cdot I_{\beta}^{*}), \tag{17}$$

$$Q = \frac{3}{2}(-V_{\beta}^{*} \cdot I_{\alpha}^{*} + V_{\beta}^{*} \cdot I_{\alpha}^{*}). \tag{18}$$

## 5. Testing the Influence of Various Cases for Proposed Power Controller

The increasing use of sensitive and critical equipment in electrical grids requires to be served by high voltage/power quality. The hybrid power systems include more and more unbalanced and nonlinear equipment that negatively affect power quality. Taking into account all these factors associated with power quality problems, DSOGI-PLL based PR controller provides a solution that can enhance the voltage/power quality at both grid and customer sides [5]. The performance of the proposed power controller based on DSOGI-PLL is validated, confirmed and compared with SRF-PLL by simulation studies using the PSCAD/EMTDC analysis program in various case studies as follows;

- Case 1 - Testing the influence of single-phase fault
- Case 2 - Testing the influence of phase to phase fault
- Case 3 - Testing the influence of the impact of voltage harmonics
- Case 4 - Testing the influence of unbalanced voltage condition

**Case 1 - Testing the influence of single-phase faults:**

The performances of the DSOGI-PLL based PR controller under unbalance caused by a single phase (A) to ground fault are depicted in Fig. 8. At 0.4 s during 0.2 s, the phase A to ground fault occurs and phase A voltage decreases to 40 % of its nominal value. The fluctuations and ripple error on orthogonal (d-q) signals and power are compared and graphically shown in Fig. 8. The ripple errors have the double-frequency ripple (2 w) during unbalance with the SRF-PLL based PR controller. The simulation results show that the proposed DSOGI-PLL based PR controller minimizes voltage and current ripple errors on (d-q) signals almost to zero level when compared with the SRF-PLL based PR controller.

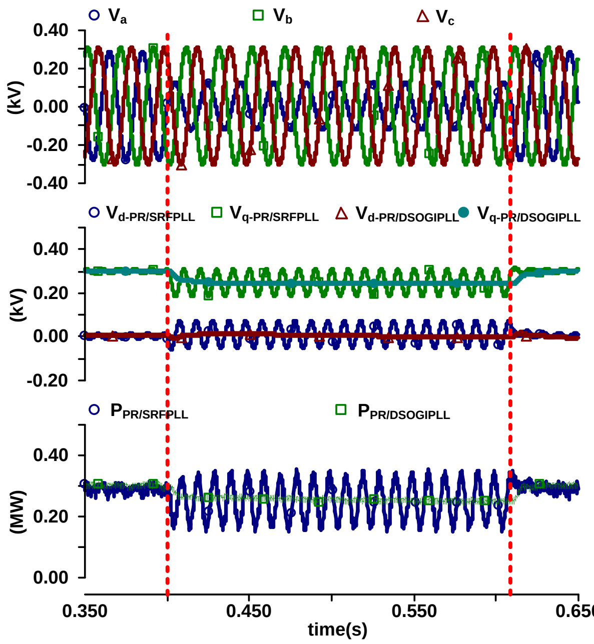


**Fig. 8:** SRF-PLL and DSOGI-PLL based PR controllers under single-phase fault.

**Case 2 - Testing the influence of phase to phase fault:**

The performances of the PLLs based PR controller in the case of unbalance caused by phase to phase fault are depicted in this case. At 0.4 s, phase A and phase B voltages decrease to 49 % of their nominal values. The results for orthogonal signals of PLLs (SRF-PLL and DSOGI-PLL) based PR power controllers are given in Fig. 9. The DSOGI-PLL is compared with SRF-PLL in order to analyse the performances. The first named provides good performance to eliminate ripple errors (double frequencies signals) on power control and orthogonal voltage signals. The current and voltage amplitudes measured in case of SRF-PLL based PR controller are highly sensitive to unbalance conditions.

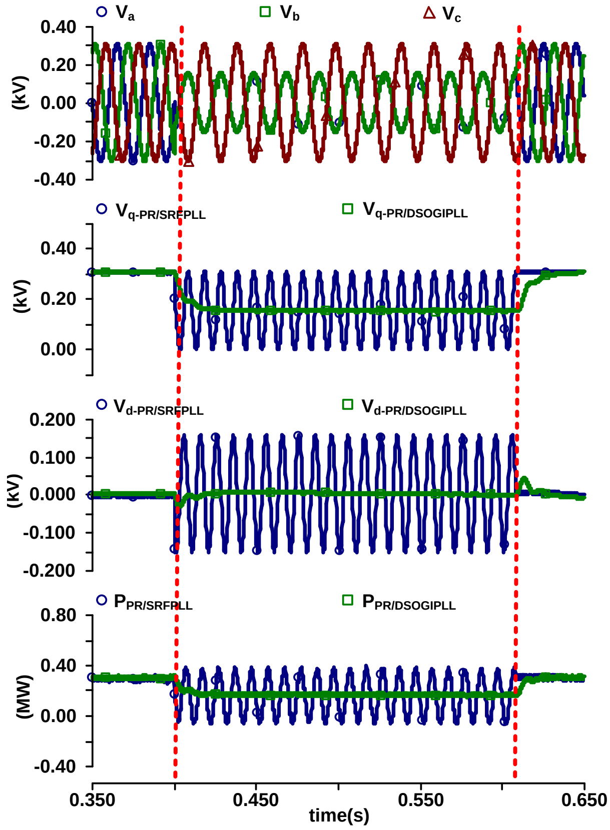


**Fig. 9:** PLLs based PR controllers under phase to phase fault.

### Case 3 - Testing the influence of the harmonic condition:

Although SRF-PLL based PR controller effectively performs to mitigate harmonics in the system, it is not enough to eliminate control signal errors caused by harmonics. Therefore, the DSOGI-PLL based PR controller is proposed to overcome these problems. The effect of voltage harmonics on the performances of SRF-PLL and DSOGI-PLL based PR controllers are analysed and compared graphically in Fig. 10. It can be clearly observed that the DSOGI-PLL based PR controller ensures higher performance in the elimination of harmonic ripple errors (6 w frequency ripple) in signals.

As shown in Fig. 11, the three-phase inverter output currents $I_a$, $I_b$ and $I_c$ are also tested under voltage harmonics. The simulation results show that the proposed power controller accomplishes to mitigate harmonic components to 0.35 % THD. It also reduces ripple errors and fluctuations in amplitudes of power and orthogonal signals.

### Case 4 - Testing the influence of unbalanced voltage condition:

Benchmarking performances of orthogonal signals and active power related with controllers are compared

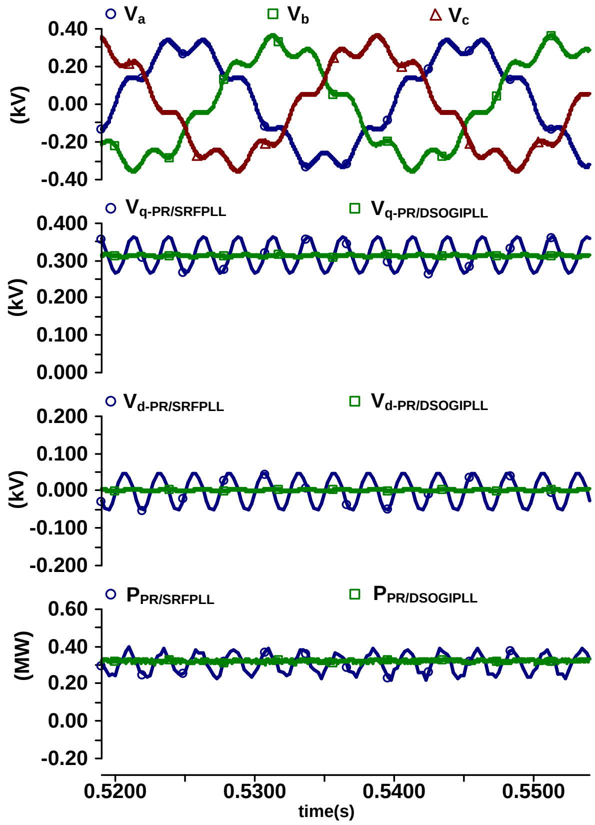


**Fig. 10:** The performance of orthogonal signals and power under voltage harmonics.

in Fig. 12. At 0.4 s during 0.2 s, phase B voltage increases by 17.8 %, phase A decreases by 49 % and C decreases by 12 %, voltages are given according to the nominal grid voltage. The impact of unbalanced grid voltage is observed in power and orthogonal voltage signals. As can be seen from Fig. 12, the proposed power controller based on DSOGI-PLL eliminates the double-frequency ripple (2 w) in the amplitudes of orthogonal signals and active power. It ensures high accuracy and fast dynamic response.

## 6. Conclusion

This paper presents and compares two PR power/current controllers based on different synchronisation algorithms for mitigating the influences of grid disturbances on control of three-phase inverter connecting a hybrid power system. Hybrid power system sources consisting of solar cell and wind turbine are modelled, analysed, and connected by power electronic devices to the DC bus separately. The proposed power controller based on DSOGI-PLL ensures better solution and overcomes power quality problems such as voltage sag/swell, voltage unbalance and harmonics. The control of three-phase inverter is examined and analysed under various case studies, such as grid

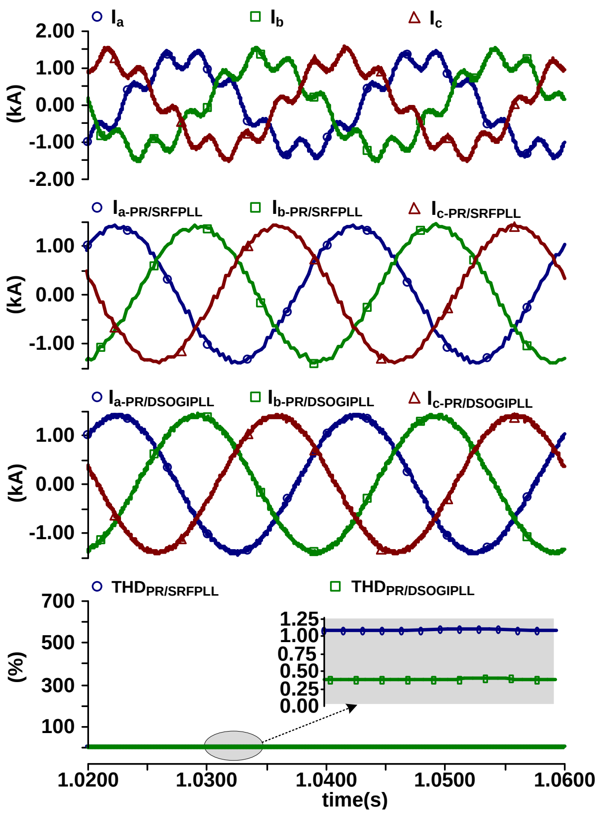


**Fig. 11:** Benchmarking performances of SRF-PLL and DSOGI-PLL based PR controller for inverter output current.

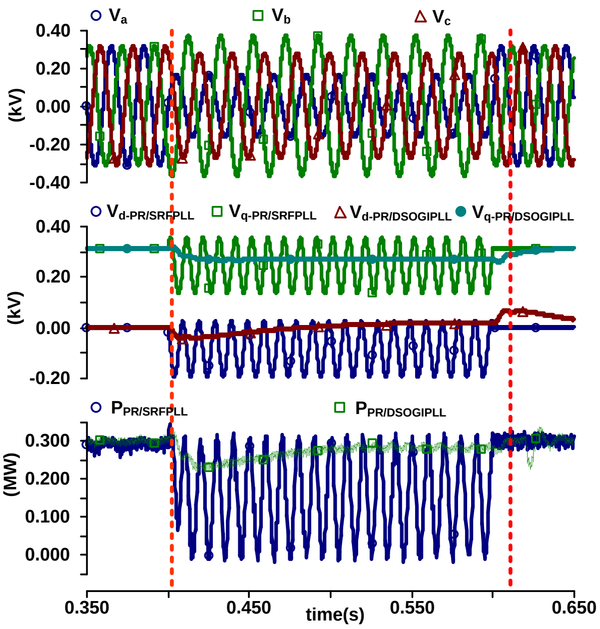


**Fig. 12:** PLLs based PR controller for unbalanced voltage.

faults, harmonic distortions, and unbalanced voltage conditions. The results show that the proposed DSOGI-PLL and PR based power controller removes double frequency (2 w) ripples and six times frequency (6 w) ripples under unbalanced and distorted grid voltages in amplitudes of orthogonal voltage d-q signals and active power. Compared with classic PLL based PR controllers, the case results reveal that the DSOGI-PLL based PR controller ensures robustness, accuracy, and fast dynamic response.

This paper is a comprehensive survey with the aim of enhancing the knowledge of the researcher who wants to research in this field.

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